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US Army Research Laboratory

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14. ABSTRACT Recently there has been increasing interest in the development and distribution of low-cost modular electroencephalography (EEG) systems that can be assembled and used by scientists, physicians, and even novices for widespread application, including real-world neuroimaging, in-home medical monitoring, and gaming/entertainment, across a diverse user community (e.g., OpenBCI). Accordingly, the purpose of this pilot project was to design and test the applicability of such a prototype EEG headset consisting of a set of Velcro straps with designated locations for integrating various potential types of EEG sensors. We provided the participants with written instructions for assembling the straps and asked them to apply both the prototype system and a standard commercial system on 2 identical head models on 3 different days. We digitized the locations of the sensor locations and analyzed electrode distances relative to standard reference locations on the head models. Results indicated that the participants were able to consistently apply the system with acceptable differences in accuracy and precision (<1-cm error) for most of the tested electrode locations, which was comparable to those achieved using a standardized electrode cap with fixed electrode locations, although significant differences were observed for some locations between prototype and standard systems. In this report we also discuss implications and needs for future research.					
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Executive Summary

Given the increasing interest in recording electroencephalography (EEG) in real-world environments, researchers are pursuing studies using ambulatory EEG systems designed to record brain dynamics in more-realistic task environments. These studies improve the ecological validity of brain imaging research and provide more-practical solutions for in-home medical monitoring and brain-computer interface applications. However, many of the commercially available portable systems are relatively expensive, require proprietary software to function, lack flexibility or modularity, and require trained researchers or clinicians to apply the system as well as record, analyze, and interpret the data. Accordingly, the purpose of this pilot project was to design a low-cost, nonproprietary, modular prototype EEG system and assess whether it would be feasible or practical for a group of diverse individuals to accurately and consistently apply this prototype system on a head model. This question was addressed by having participants apply both the prototype system and a standard commercial system on head models during each of 3 repeated test sessions. Electrode locations were digitized and analyzed relative to standard reference locations of the International 10-20 electrode placement system and relative to within- and between-subject average electrode positions across the 3 test sessions.

Overall, the results revealed significant differences in electrode locations between the prototype EEG system and the standard reference system. However, these differences varied widely according to the individual electrode position being analyzed. In the case of some electrode positions, users obtained a relatively high degree of precision for both systems, suggesting useful avenues for future improvements involving such anchor points.

We conclude that it would be feasible for individuals, even with little or no prior knowledge of EEG, to consistently apply a system resembling the prototype design with acceptable differences in accuracy and precision (<1-cm error) for most of the tested electrode locations, comparable to those achieved using a standardized electrode cap with fixed electrode locations.

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1. Introduction

1.1 Background

The development of electroencephalography (EEG) for human brain imaging dates back to the late 1920s (Berger 1929; Coenen and Zayachkviska 2013). Berger applied saline-soaked gauze pads on posterior regions of the scalp and identified what is known today as alpha oscillations—rhythmic electrical activity occurring between 8 and 13 Hz and associated with closed eyes and/or relaxation. However, at that time there were no standards for placement of electrodes on the scalp for recording surface potentials using EEG. Decades later, Jasper (1958) introduced a standardized system for placing surface electrodes on the scalp based on cranial landmarks on the skull and a geodesic grid proportional to the size and shape of the skull. This system was called the International 10-20 system and implemented to provide a reproducible method for recording EEG data across studies and laboratories. The numbers 10-20 refer to the relative distances between neighboring electrodes at intervals of 10% or 20% with respect to standard landmarks on the skull. The 10-20 system for standard electrode placement has been the accepted system in clinical and laboratory EEG research since then, although more-recent advances have been made to accommodate higher-density electrode montages like the 10-10 (Chatrian et al. 1985) and 10-5 systems (Oostenveld and Praamstra 2001).

Traditionally, EEG has been predominantly confined to laboratory or clinical settings in which the research participants have been instructed to sit quietly and minimize eye blinks and movements while performing a given task. Such constraints are typically imposed to minimize artifacts generated by muscle activity and movement of electrode wires, which can render the EEG data uninterpretable. However, technology and signal processing advances have improved over the decades, giving rise to ambulatory EEG in the early 1970s (Ives and Woods 1975) and bringing EEG out of traditional laboratory environments. Contemporary ambulatory EEG systems are designed to record brain dynamics in more-realistic task environments to improve the ecological validity of brain imaging research and provide more-practical solutions for in-home medical monitoring and brain-computer interface (BCI) applications. For example, applications have been identified in operational neuroscience, neuroergonomics, neural prosthetics, detection of traumatic brain injury, sleep monitoring, neurofeedback, gauging real-world stress, and the video game industry to name a few (Gargiulo et al. 2010; Lin et al. 2010; Chi et al. 2012; Debener et al. 2012; Lance et al. 2012; McDowell et al. 2013a, 2013b; Rapp et al. 2015).

1.2 The Need for Real-World Neuroimaging

Today there is a demand for ambulatory/wireless EEG systems to address a wide variety of research and clinical needs, in particular in ecologically valid real-world environments. Most of the EEG systems commercially available are relatively expensive, require proprietary software to function, have limited numbers and locations of electrodes, and require trained researchers or clinicians to apply the system and to record, analyze, and interpret the data. Further, many of the currently available ambulatory/wireless systems have been designed for a specific purpose or user group and do not conform to established recording guidelines or standards (e.g., some systems designed to be used during video game play). One such issue is the positioning of electrodes in the sensor "headset" and their exact scalp location once placed on a participant's head. Many of these ambulatory/wireless EEG systems do not conform, or only loosely conform, to the standard International 10-20 system for positioning electrodes on the scalp, which makes it difficult or impossible to relate the data recorded from such systems to that recorded from conventional EEG based on the International 10-20 system. Thus, the challenge is to develop products that are less expensive, easy to prepare and record data, use open-source software, and allow for modular or flexible configuration of electrodes consistent with the standardized electrode mapping on the skull (i.e., 10-20 montage).

In recognition of all these issues, McDowell et al. (2013b, p. 2) reported that there is still a need for "the development and distribution of low-cost, modular electroencephalography (EEG) headsets, which can be assembled and used by a novice...including the development of [BrainComputer Interface (BCI) Technologies], [which] remains limited to a relatively small circle of scientists and technology developers and has not achieved a broader focus within the greater [science and technology] development community". The Defense Advanced Research Projects Agency also sought to develop such systems when they solicited proposals for their Small Business Innovation Research (SB131-002) funds (SBIR 2012), calling for portable EEG that is inexpensive, easy to use, and available to every classroom. One of the awards led to the formation of OpenBCI (OpenBCI 2013) in 2013, an open-source community aiming to mass produce EEG kits for the general public. Their vision statement describes their crowd-sourcing approach to BCI development: "The biggest challenges we face in understanding what makes us who we are cannot be solved by a company, an institution, or even an entire field of science. We believe these discoveries will only be made through an open forum of shared knowledge and concerted effort, by people from a variety of disciplines. Our vision is to realize the potential of the open-source movement to accelerate innovation in brain science."

Thus, the question or challenge that we address in this report is how an interested user, who is not part of a company or institution dedicated to the development of EEG systems, might design a low-cost, dry, wireless, lightweight, comfortable, noninvasive, and flexible EEG recording system that can be implemented in real-world environments while still conforming to established EEG recording guidelines and standards.

1.3 Purpose

Consistent with the ideas and vision of OpenBCI, we conducted a pilot study to assess whether it would be feasible or practical for a group of diverse individuals having various levels of experience with EEG to accurately and consistently apply a traditional and a novel modular EEG prototype system. Most participants, who we selected to resemble potential consumers of a potentially naive market, had no experience applying EEG caps or headsets. No verbal application instructions were provided to the participants by the experimenters. Rather, the participants were only allowed to consult simple instruction manuals for each of 2 systems: 1) a standard 64-channel Biosemi cap (Appendix A) and 2) a proof-of-principle ambulatory/wireless "Flex" system (Appendix B). The participants used the instruction manuals to assemble and apply each system independently on each of 2 identical fixed Styrofoam head models in accord with the International 10-20 system in each of 3 independent test sessions.

Compatible with McDowell et al. (2013b, p. 4), the Flex system was designed to "not require extensive setup or costly consumables, such as electrode gels . . . [that] emphasize flexibility and universality". A core concept of the system design is modularity to enable users the capability to explore creative and flexible montage configurations based on individual needs and purposes while still maintaining standards for electrode placement consistent with the International 10-20 system. For this project, we focused solely on the "headgear" design for flexible, mobile EEG recording and therefore did not implement or test actual sensors or electronic components (analog-to-digital conversion, power, and the wireless transmission). Thus, the purpose of this study was to test the feasibility of having participants, across a range of EEG experience, apply a novel, innovative, low-cost, modular proof-of-principle EEG headset design. Furthermore, how well could electrode locations of this system be accurately and reliably aligned with electrode locations of a commercial-laboratory-grade EEG system in accord with the standard International 10-20 system?

2. Methods

2.1 Participants

Twelve normal healthy male participants (ages 22–48) were recruited to apply the 2 EEG systems on 2 separate but identical Styrofoam head models. This study was exempt from review by the Human Use Committee, which considered this study to consist of minimal-risk testing and evaluation of materiel. Therefore, the participants were not required to sign an informed-consent form. Nevertheless, confidentiality has been protected and the participants were informed that they were free to withdraw from the study at any time without penalty or negative consequences.

2.2 Materials and Instruments

Two EEG headsets were used in this study: 1) a standard 64-channel Biosemi electrode cap (Biosemi 2015) and 2) a prototype 19-channel Flex system based on elastic straps fabricated from Velcro material (resembling a potential “EEG kit” for inexperienced users). Figure 1 illustrates both systems, and Appendix C provides a computer-aided drawing of the Flex system components. A 3-dimensional (3-D) digitization system, the zebris electrode positioning (ELPOS) system (zebris 2015) was used to measure positions of electrodes once participants placed them on the head models, and a stopwatch was used to time applications of each EEG system to each head model.

Fig. 1 Biosemi (left) and Flex (right) systems

2.3 Design Concept of the Flex Headset

The Flex system, consisting of 8 elastic Velcro straps, was designed in-house as a stretchable one-size-fits-all headset to allow for symmetric sensor coverage of the whole head when placed on the head using the same guidelines and standard landmarks on the skull as established by the International 10-20 system.

A base circumferential strap (also called the "circular" or "circle" strap in the instructions, Appendix B) is first placed on the head along the transverse/axial plane positioned just above the eyebrows in the front and the inion (Iz) in the back of the head (based upon an approximation of 10% of the distance from nasion [Nz] to Iz along the sagittal plane) and just above the left and right pre-auricular points (based upon an approximation of 10% of the distance from the left to right pre-auricular points along the coronal plane). A chinstrap is then attached with Velcro to the circumferential strap, slightly anterior to the pre-auricular points, passing under the base of the chin along the coronal plane to prevent the circumferential strap from moving. Next, a longitudinal (or "lengthwise") strap is attached from Nz to Iz along the sagittal plane and a transverse (or "sideways") strap is attached from left to right pre-auricular points along the coronal plane. The intersection of these 2 straps marks the vertex of the scalp (corresponding to 10-20 position midline central [Cz]; 50% of distance from Nz to Iz in the sagittal plane and 50% of the distance between pre-auricular points in the coronal plane). Finally, 4 short connector (or segment) straps are attached from the longitudinal strap to the circumferential strap over each of the 4 quadrants of the head (demarcated by the longitudinal and transverse straps) using the following guidelines. In the left/right frontal quadrants, connector straps are attached at the midpoint of the distance from the vertex of the scalp to the Nz along the longitudinal strap to the midpoint of the distance from the left/right pre-auricular point to the Nz of the circumferential strap. In the right/left posterior quadrants, connector straps are attached at the midpoint of the distance from the vertex of the scalp to the Iz along the longitudinal strap to the midpoint of the distance from the left/right pre-auricular point to the Iz of the circumferential strap. Figure 2 diagrams a 2-dimensional top-down view of the resultant configuration of the straps and how the intersections of these straps forms the basis for the positioning of 17 of the original 21 electrode positions congruent with the 10-20 system (left/right nasopharyngeal and left/right cerebellar positions were omitted).

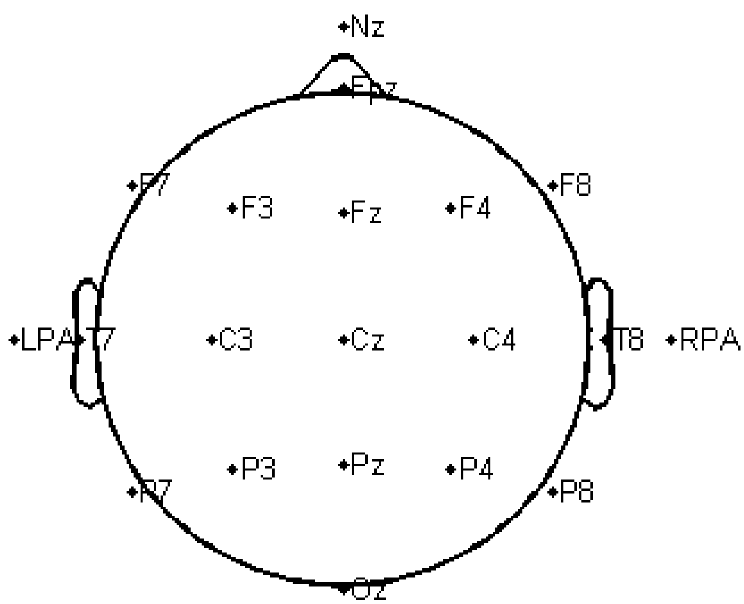

Fig. 2 Fiducials and electrode locations digitized for each EEG system. Fiducials: left pre-auricular [LPA], Nz, and right pre-auricular [RPA]; electrode locations: midline frontopolar [FPz], midline frontal [Fz], midline central [Cz], midline parietal [Pz], midline occipital [Oz], left frontal [F3, F7], left central [C3], left temporal [T7], left parietal [P3, P7], right frontal [F4, F8], right central [C4], right temporal [T8], right parietal [P4, P8].

Actual electrodes were not embedded in or attached to the Velcro straps; however, they would be included in a later stage of development. Our objective here was to determine whether the basic design concept of the Flex headset could be applied to a head model and conform to the standards of the International 10-20 system. Five electrode positions (FPz, T7, T8, Oz, and Cz) were defined based on intersections of the lattice of main straps (circular/lengthwise/sideways). Twelve electrode positions (Fz, F3, F4, F7, F8, C3, C4, Pz, P3, P4, P7, and P8) had to be estimated at midpoints of the 4 short connector straps or of sections of the larger straps. Also, for each head model, 3 fiducials (Nz and LPA/RPA locations) were marked by experimenters before initiating the experiment using pushpins to ensure the same fixed reference locations were marked across all participants and sessions.

System modularity was conceived to enable flexibility in the configuration of various montages based on the individual user needs. For example, if a particular researcher was interested in developing a specific BCI application and only needed to record data from specific brain regions that are known to provide the best signal for that application, a "regional" montage could be configured to reduce setup time and conserve computing resources. That is, the researcher could apply a subset of the straps to cover only the motor regions of cortex (or only the posterior visual regions or frontal executive regions). One could also conceive of experiments or applications in which data from only the left (or right) hemisphere is of interest. Although many possibilities exist, we asked the participants to apply the Flex system using only the montage for whole-head coverage.

2.4 Procedures

2.4.1 Application of EEG Systems

Participants were brought into the lab and were provided with components and application instructions for each system. They were asked to participate in 3 sessions separated by at least one day and at most one week. In each of the 3 sessions, the participants were asked to follow the procedures described in the respective instruction manuals for applying each system on each of 2 identical Styrofoam head models. The order in which the participants were asked to apply the 2 EEG systems was counterbalanced across participants and sessions to minimize order effects. Experimenters also recorded, using a stopwatch, the elapsed time for the participants to apply each of the EEG systems. After the participants completed the application of both systems, they were dismissed and the experimenters measured the electrode positions (in Cartesian coordinates) of each EEG system using the zebris ELPOS system (Fig. 3).

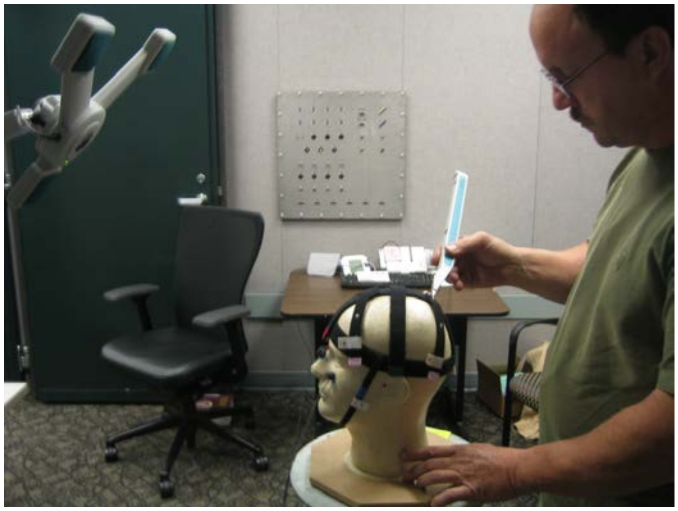

Fig. 3 Digitization of electrode positions with the zebris ELPOS ultrasonic system

2.4.2 Measurement of Electrode Positions

There are 2 relevant sources of error in determining electrode positions for this study: 1) placement of the EEG systems on the Styrofoam head models by the participants and 2) digitization of electrode locations for each system by the experimenters. Applying the Flex system required more steps for the participants so the instruction manual was necessarily longer and more complicated than that required for application of the Biosemi system. This is because the Flex system required the assembly of 8 separate component straps while the Biosemi cap is preassembled and applied as one component. Digitization of electrode locations for the Flex system was also more difficult for the experimenters because it did not house actual electrodes and the hypothetical electrode locations were operationally defined by the intersections of straps for some electrodes (FPz, Cz, Oz, T7, and T8) and estimated distances between intersections of straps for other electrodes (Fz, F3, F4, F7, F8, C3, C4, Pz, P3, P4, P7, and P8).

Therefore, to minimize the effects of these 2 sources of error on our interpretation of the comparison analyses, we analyzed the data in 3 different ways based on 3 different reference coordinate frameworks: 1) expert-derived, 2) between-subjects, and 3) within-subjects referencing schemes. We first verified that none of the participants applied either system backward, sideways, or otherwise drastically different from the instructions provided (Appendixes A and B). By plotting the 3-D positions of the electrodes digitized for each of the 3 sessions for each participant and system, we were able to confirm that all of the participants adhered to the instructions and applied the systems to the head models correctly and consistently over the 3 sessions. (Figure 4 shows electrode positions digitized for each system and session for an example participant.)

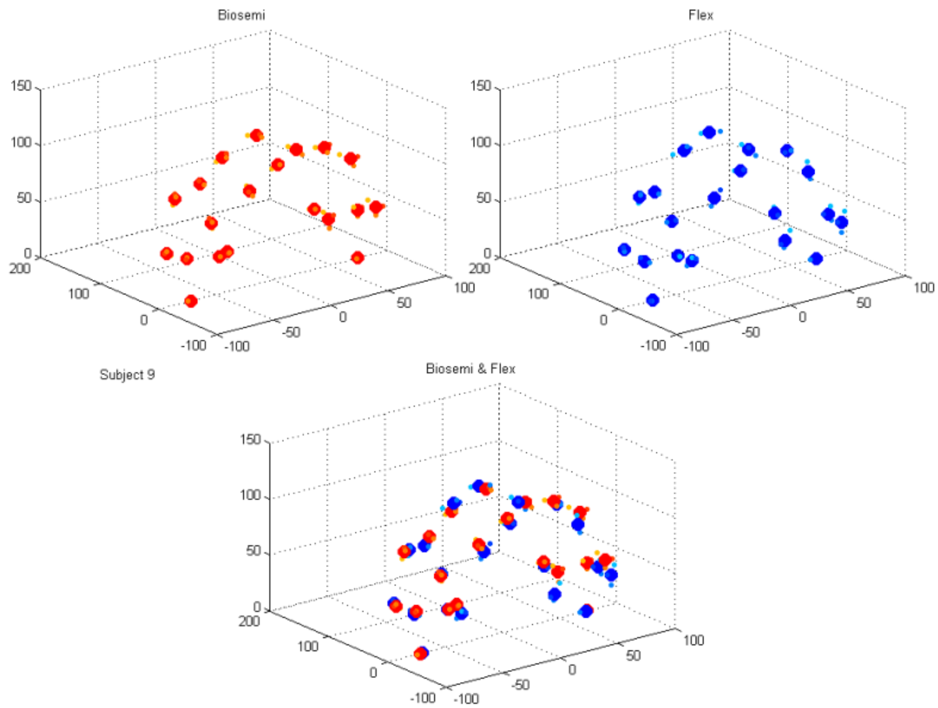

Fig. 4 Digitized electrode positions of the Biosemi (red, top left), Flex (blue, top right), and both systems combined (lower middle) for an example participant. Small circles represent measures at each of the 3 sessions and large circles represent the mean positions over the 3 sessions (X, Y, and Z axes reflect distance in millimeters).

2.5 Design and Analysis

With 12 subjects participating in the described experiment, for each headset we were presented with 36 sets of coordinates (x, y, z coordinates for each electrode from 12 subjects × 3 sessions) specifying the electrode positions. In addition, a "baseline" digitization of coordinates was obtained by an EEG expert for comparison.

Euclidean distance in 3 dimensions was deemed to be a reasonable approximation to the length on the curved surface of the Styrofoam head model at the scale of the electrode displacements measured. A metric based on the nonspherical geometry of the Styrofoam head would have been well outside the scope of the experiment and would add little to the analysis. For each electrode position, we were interested in both the accuracy of the 12 subjects' placement relative to standard 10-20 electrode locations and the variability (precision) of the electrode locations for each electrode and system across all subjects and sessions. In the latter case, it is important to take into account the sample mean of each electrode's position across subjects and/or sessions. The mean position of a set of coordinate triples is referred to as $(\bar{X}, \bar{Y}, \bar{Z})$. Distance between the i-th measurement and a mean position is expressed as

$$d_i = \sqrt{(X_i - \overline{X})^2 + (Y_i - \overline{Y})^2 + (Z_i - \overline{Z})^2}. \quad (1)$$

We used 3 different sets of reference positions $(\bar{X}, \bar{Y}, \bar{Z})$ of electrodes to perform 3 different analyses.

2.5.1 Expert-Derived Reference

First, an expert marked electrode locations on a Styrofoam head model, and these marks were digitized and stored as an "expert-derived" reference. In this case, we were interested in observing how well subjects fitting the 2 EEG systems were able to match an independently defined or absolute reference.

2.5.2 Between-Subjects Reference

Second, we computed the Euclidean mean of all samples across subjects and sessions for each electrode and system, giving a single centroid location for each electrode for each system. Examining electrode placement distances from these centroids provides insight into the within-system precision. For example, a particular system might exhibit more consistency in the electrode placements across subjects, or certain electrode positions might be more consistent across subjects.

2.5.3 Within-Subjects Reference

Finally, we calculated the Euclidean mean of the 3 sessions for each subject, system, and electrode. In this case, a set of centroids was derived for each unique user consisting of their mean electrode placement for each electrode, system, and session. In this instance we intended to examine how well an individual user was able to replicate locations of electrode positions within a particular system across the 3 sessions. Here, each centroid was generated by only 3 position vectors corresponding to the positions obtained by a subject on an individual electrode and system across 3 sessions.

We performed 3 separate, 4-factor, mixed analyses of variance tests (ANOVAs) (2 systems × 3 sessions × 20 electrodes × 12 subjects) on distances relative to the expert-derived, between-subject-derived, and within-subject-derived reference electrode positions. Systems, sessions, and electrodes were fixed effects, and subjects were a random effect in the statistical models. For each of the 3 described methods of measuring electrode distances from 3 different reference positions, we also performed a paired Welch's t-test on the distributions of electrode positions collapsed across subjects and sessions, comparing said distributions between the Biosemi and proposed Flex systems.

2.5.4 Time for Participants to Complete Application of EEG Systems on a Standard Head Model

We also examined the time required for the participants to complete the application of each system during each session. A stopwatch was used to record the initiation of application separately for each system, which began after the experimenter cued the participant and stopped when the participant finished applying the first system. After applying the first system, and when the participant indicated he/she was ready, the process was repeated for the second system (counterbalanced across sessions and participants). System application times were then analyzed using a 2 (systems) × 3 (sessions) × 20 (electrodes) within-subjects design.

3. Results

3.1 Expert-Derived Reference

We compared the Euclidean distance of electrodes from a set of expert-derived reference coordinates for each system across subjects and sessions. Mean distances from the reference positions are plotted in Fig. 5 for each electrode and system collapsed across sessions. The previously described 4-factor ANOVA found a significant effect for the EEG system between the Biosemi and Flex systems ($F = 40.83$, $p < 1E-6$), where Biosemi electrodes were on average 18.4 mm from reference positions while Flex electrodes were on average 20.1 mm from reference positions.

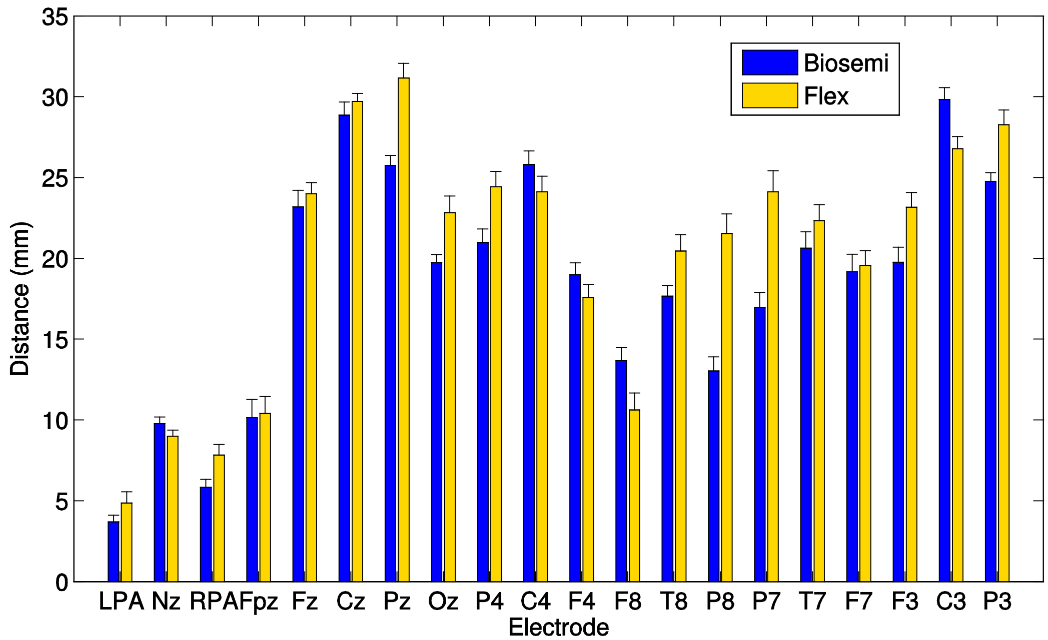

Fig. 5 Average Euclidean distance of electrodes from expert-derived position, by electrode. The error bars indicate the standard error of the mean for measurements on each electrode.

Distributions of distances from the expert-derived electrode position were significant between systems for a subset of tested electrode positions according to a paired Welch's t-test comparing sample distributions for electrodes and by system. Electrodes where the Biosemi system position was significantly closer to the expert-derived positions included RPA ($p = 0.0183$), Pz ($p = 3.79E-6$), Oz ($p = 0.0094$), P4 ($p = 0.0073$), T8 ($p = 0.0235$), P8 ($p = 2.14E-7$), P7 ($p = 2.88E-5$), F3 ($p = 0.0103$), and P3 ($p = 0.0012$). Electrodes where the Flex system position was significantly closer to the expert-derived positions included F8 ($p = 0.0256$) and C3 ($p = 0.0012$).

3.2 Between-Subjects Reference

As discussed in the previous section, we were interested in examining the precision of electrode positions obtainable relative to centroids derived either across or within subjects. In the first instance, to test the inter-subject consistency, a centroid was derived for each electrode (and system) across all subjects and sessions by taking the average of all Euclidean measurements for each electrode and system. Then the Euclidean distance of each measurement was computed for each sample from its associated centroid. We again observed a significant difference between systems according to the 4-factor ANOVA test ($F = 49.39$, $p < 1E-6$); users generally obtained a lower distance to the overall electrode centroid using Biosemi versus Flex (average distances were 7.3 and 9.2 mm, respectively). Mean distances from the between-subjects reference positions are plotted in Fig. 6 for each electrode and system collapsed across sessions.

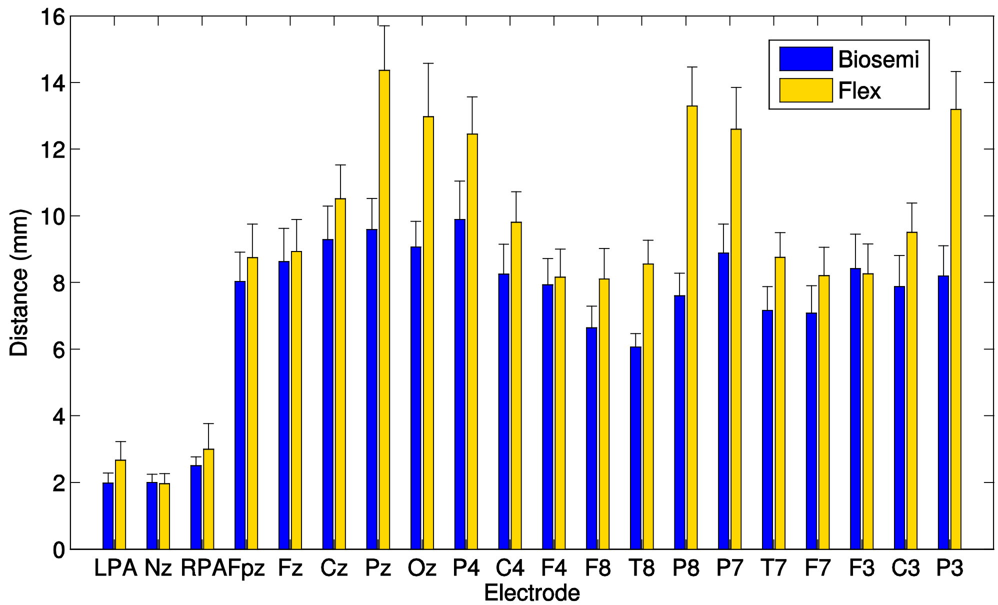

Fig. 6 Average Euclidean distance of electrodes from cross-subject centroid, by electrode. The error bars indicate the standard error of the mean for measurements on each electrode.

While there was a clear effect for the EEG system in the comparison between the Biosemi and Flex systems, certain electrodes were quite close in terms of user deviation from the within system/across subject centroid, especially Nz along with Fpz, Fz, F4, and F3.

A paired Welch's t-test comparing systems by electrode yielded particularly low p-values for electrode positions Pz ($p = 0.0045$), Oz ($p = 0.0305$), T8 ($p = 0.0033$), P8 ($p = 7.86E-5$), P7 ($p = 0.017$), and P3 ($p = 9.32E-4$), with lower p-values indicating a higher probability that the observations were drawn from different distributions. In all of the 6 listed cases, Flex system electrode placement tended to be further from the within-system centroids than the Biosemi system placement, constituting evidence that, for these 6 electrode positions, users applying the Biosemi system may obtain more consistent results than a centroid derived across users.

3.3 Within-Subjects Reference

We also examined the intrasubject consistency of electrode placement by comparing observations to centroids obtained by averaging the 3 session measures for each subject, system, and electrode. This tests the precision an individual subject is able to obtain for each electrode. In so doing, we allow for differences between subjects in the perception of where each electrode should be placed. Again, we observed a significant effect between systems according to the 4-factor ANOVA test with electrodes and systems as factors ($F = 43.37$, $p < 1E-6$). The average distance of an electrode from the user-specific centroid was 5.2 mm in the Biosemi system and 6.3 mm in the Flex system. However, the variances in the case of both averages were quite large (>10 mm) due to differences in obtained distances by electrode. Mean distances from the within-subjects reference positions are plotted in Fig. 7 for each electrode and system collapsed across sessions.

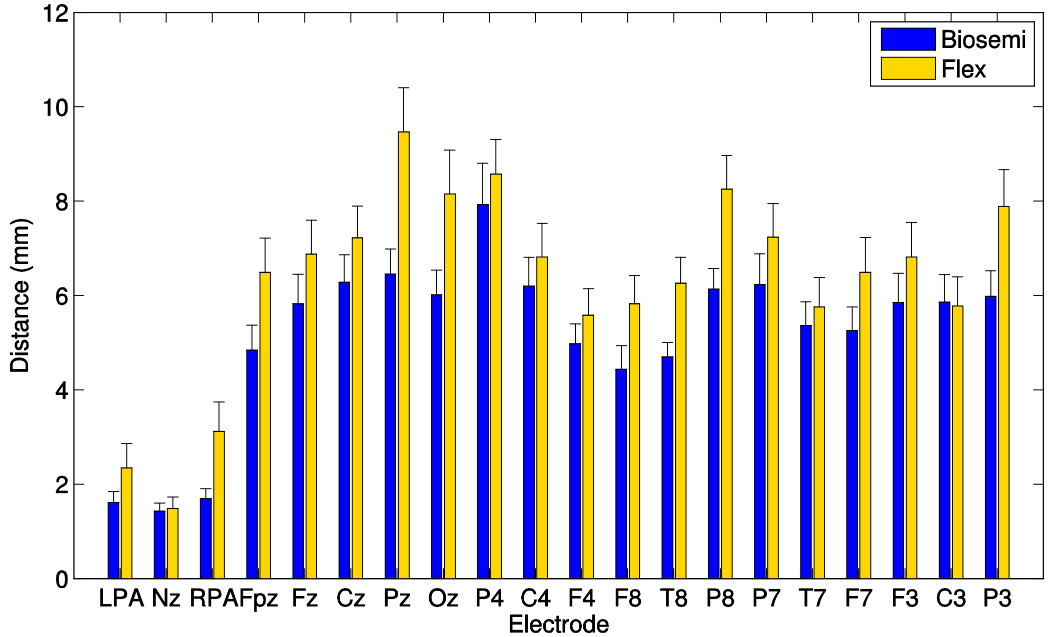

Fig. 7 Average Euclidean distance of electrodes from within-subject centroid, by electrode. The error bars indicate the standard error of the mean for measurements on each electrode.

Again, while significant effects were observed according to measures across the system, we found that certain electrode distance distributions were strikingly similar across systems. In particular, relatively low average electrode distance in the LPA, Nz, and RPA positions in both the across- and within-subject centroid experiments suggest the usefulness of such positions as anchor points in subsequent analyses.

A paired Welch's t-test measuring the likelihood that electrode positions relative to a within-subject centroid were significantly different by system again revealed several low p-values for certain electrode positions. Notably, the RPA position differences had a p-value of 0.0334, indicating that subjects using the Flex system likely obtained less precision on this electrode relative to their individual average placement position than they obtained with the Biosemi system.

On the other hand, the p-value of the same paired Welch's t-test for electrode position P7 (comparing Biosemi and Flex systems) was no longer significant ($p = 0.2979$), and the mean of these observations was much smaller than the mean of observations relative to an across-subject centroid. This indicates that subjects were generally able to place the P7 electrode relatively close to their own centroid for this location using the Flex system. However, the distribution of subjects' P7 centroids were relatively spread out, resulting in larger distances for individual subjects' P7 positions relative to the single cross-subject P7 centroid. More simply, we suggest that the subjects' perceptions of where the P7 electrode should be placed using the Flex system tended to vary between subjects, resulting in higher within-subject precision and lower across-subject precision.

The 4-factor ANOVAs described in the previous section indicated significant main effects not only in the system factor, but also in electrodes and subjects. In all 3 manners of describing distance—from the expert position, across-subject centroid, and within-subject centroid, we found main effects in electrodes ($F = 146.43$, $p < 1E\text{-}6$; $F = 21.61$, $p < 1E\text{-}6$; $F = 21.48$, $p < 1E\text{-}6$, respectively) and subjects ($F = 11.25$, $p < 1E\text{-}6$; $F = 9.88$, $p < 1E\text{-}6$; $F = 24.03$, $p < 1E\text{-}6$, respectively).

The electrode main effect in the case of distance measured relative to an expert-derived position exhibited a high F-value relative to the same effects in the case of distances relative to across-subject and within-subject centroids, which is likely indicative of the variation between the expert electrode positions and the target positions perceived by subjects for some electrodes. Significant main effects by subject in all 3 proposed measures of electrode placement indicate meaningful differences in subject performance.

No significant main effects for the session factor were discovered in the ANOVA, indicating that there may not be a strong learning effect on subject performance in either the Biosemi or Flex systems (a result that was consistent with a similar 3-way ANOVA that isolated the systems).

3.4 Time for Participants to Complete Application of EEG Systems

A 2 (systems) × 3 (sessions) repeated-measures ANOVA revealed significant main effects for both systems: $F(1,9) = 136.79$, $p < 0.001$; sessions, $F(2,18) = 57.57$, $p < 0.001$; and their interaction, $F(2,18) = 31.54$, $p < 0.001$. The main effects for system revealed that participants were much faster at applying the Biosemi system (76.93 ± 5.11 vs. 314.97 ± 23.27 s), and the main effect for sessions revealed that the time to apply the systems over sessions decreased (session 1 = 283.95 ± 18.22 s; session 2 = 162.80 ± 16.29 s; session 3 = 135.1 ± 12.278 s). The interaction revealed decreased time to apply the systems from session 1 to 3, but the reduction was greater for the Flex system (Fig. 8).

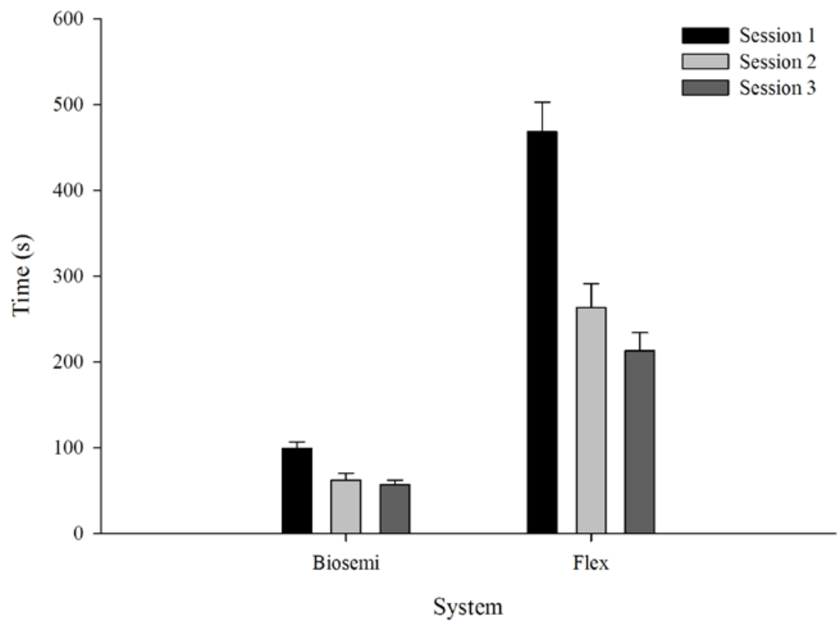

Fig. 8 Time for participants to apply EEG systems by sessions (in seconds). Error bars are standard errors of the means.

4. Discussion and Conclusions

Overall, the results of this test and evaluation of electrode positions of a prototype ambulatory/wireless modular EEG recording system indicate a significant difference between systems regarding the accuracy of electrode placement relative to an expert reference and precision of placement relative to within and across subject centroids. Users of the Biosemi system generally obtained greater precision in electrode placements; however, differences across subjects and sessions were not consistent or uniform across electrodes, as revealed by the significant main effect of electrodes in the ANOVA.

While the system main effect was significant, it is not unexpected given that the Biosemi cap consists of embedded electrodes at fixed inter-electrode distances while the Flex system consists of a series of straps that have to be assembled with each application. Despite this difference between the 2 systems, for even the largest differences in electrode distances for specific electrodes, the difference between the means of 2 systems never exceeded 1 cm. Thus, the proposed flexible system may still be of experimental value within the same tolerances that the Biosemi device is useful, especially in a case where cost and function are taken into account.

Unexpectedly, regions of greatest variability were observed over midline recording sites (Fz, Cz, and Pz) and right posterior regions (P4 and P8). It would seem that the easiest sites to align most consistently would be along the midline because they are all embedded in a single strap in the Flex system and along the center of the cap in the Biosemi system. On the other hand, as expected, the regions with the least amount of variability were observed at fiducial sites. This is to be expected because the Nz and auricular fiducials were fixed head model features. Regarding scalp electrode locations, the least amount of variability was observed in the right frontal and bilateral temporal areas. Based on these results, it is difficult to generalize a specific problem area or topography of the scalp. For example, areas with the largest variability in distances, collapsed across systems and sessions, were midline and right posterior areas while the smallest variability in distances were also right-sided but more anterior.

In a study that investigated differences in electrode positions between a commercially available laboratory-grade EEG system and 3 commercially available wireless EEG systems, Hairston et al. (2014) digitized electrode locations of a reference Biosemi system and each of 3 wireless EEG systems and compared the radii of the digitized spherical measurements at each sensor location in common between systems. Using this method, they found minimal differences across systems at the vertex (Cz) but found differences at different locations depending on the wireless system tested at midline and bilateral parietal/occipital and bilateral frontal regions. Although they used only the radii of the spherical coordinates in their comparisons, we used all 3 coordinates in Cartesian coordinates in our estimates of differences between electrode locations across systems.

According to Jurcak et al. (2007), who examined electrode locations based on 4 different sets of reference points on the scalp (Nz, Iz, and 4 different pre-auricular points bilaterally) and different recording montages (10-20, 10-10, and 10-5), temporal areas near the ears were affected most by differences in pre-auricular definitions, but deviations were less in anterior, posterior, and parietal areas. Towle et al. (1993) found that electrodes along the parasagittal plane were associated with greater measurement errors (maximum 7 mm) relative to midline electrodes, with the greatest variability observed in the temporal region (averaging 5 mm from the mean). Perhaps a reason for the relatively greater variability in midline sites in the present study was errors in application of the systems, or errors in digitization, along the sagittal central reference curve between Nz and Iz. Perhaps this error could be further reduced with more explicit attention to instructions for marking reference points on the scalp and ensuring that application of the system is in alignment with these reference points. We tend to believe that the temporal electrodes revealed the least amount of variability across systems and sessions because of the spatial proximity to the fixed pre-auricular points, marked with pushpins. The pushpins provided a reference for both participants and experimenters when applying the EEG systems and digitizing electrode positions, respectively.

These results suggest that future research will be needed to determine which areas are most troublesome to accurately and consistently localize when applying EEG for recording over standardized locations. Instructions may need refinement, and additional landmarks may need to be referenced to improve the consistency of electrode placements of a nontraditional EEG sensor headset. Spatial normalization is a difficult problem in neuroimaging research, which is important for comparing results across individuals and studies (Brett et al. 2002).

5. Limitations and Future Research

In general, we conclude that it would be feasible for individuals, even with little or no prior knowledge of EEG, to consistently apply a system resembling that of our Flex prototype design with acceptable differences in accuracy and precision (<1-cm error) from that achieved using a standardized electrode cap with fixed electrode locations. However, this study consisted of a small sample, and participants tested only on 3 occasions with one particular system on fixed head models. Thus, more-robust testing and evaluation is needed across a range of EEG system designs, head sizes, and head shapes. It would also be worthwhile to investigate improved methods for comparing EEG sensor locations, such as using a phantom head (such as a bust with embedded antennae emitting signals) that could be used to test various sensor locations and electrode properties of various EEG headgear (Collier et al. 2012). Test participants should also be tested on a greater number of trials over a longer period of time. Another matter for consideration would be the hair interference problem (Reis et al. 2014), whereby long, dense hair can interfere with contact between electrodes and skull. Optimal brain signal reception would require testing various combinations of headstrap designs and electrode designs.

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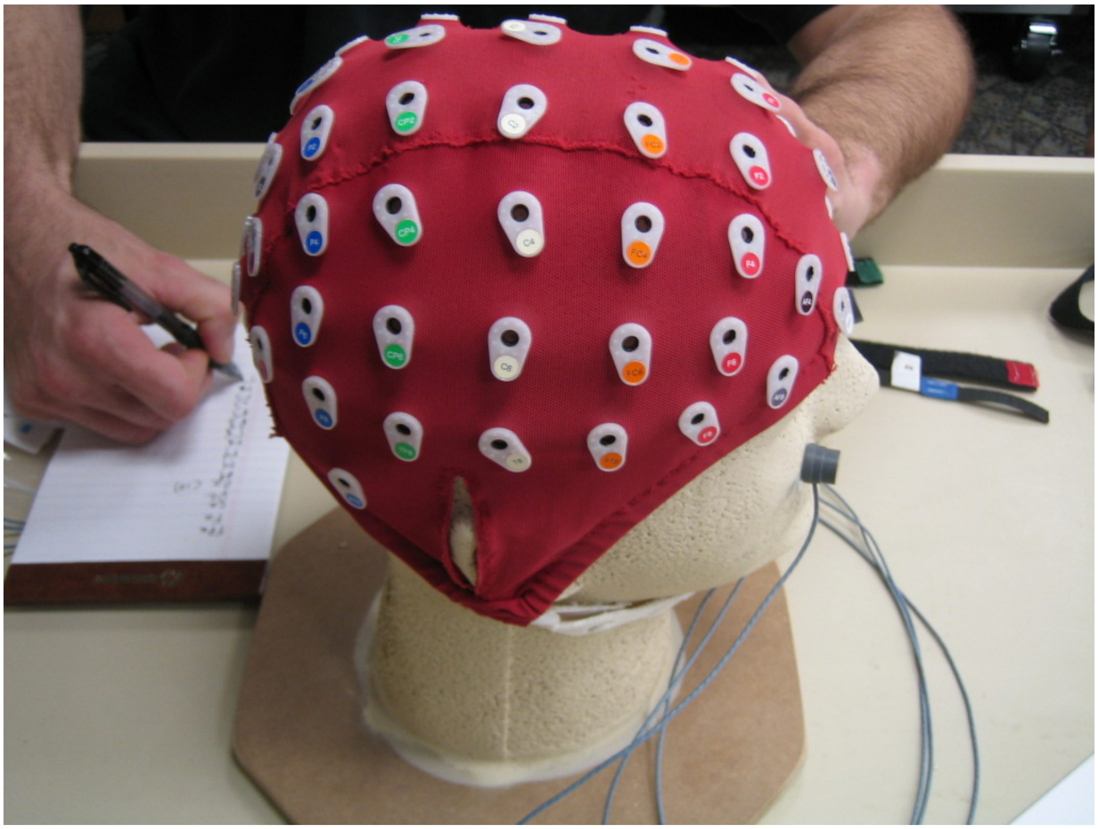
Appendix A. Biosemi Application Instructions

This appendix appears in its original form, without editorial change.

BioSemi EEG Cap application instructions



Dr,Scott Kerick

Theodric Feng

David Kuhn

Draft … Aug 2014

ARL/HRED/TNB

Find the center, front-most electrode grommet (the plastic, teardrop-shaped ring) on the cap, labeled “Fpz”

Place the grommet on the forehead, above the browridge, and aligned with the nose

Use it to anchor the cap as you stretch it over the head.

Secure the chin strap, pressing the hook & loop (or Velcro) pieces together.

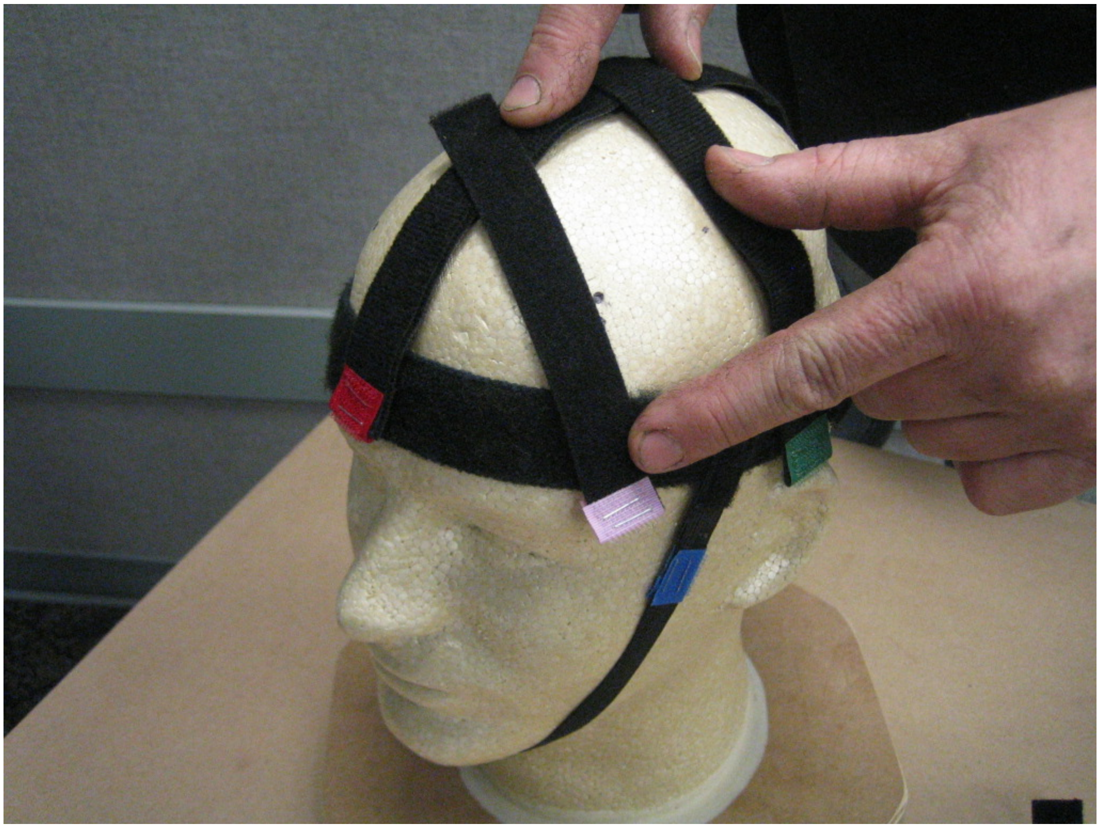
Other views of the mounted cap. (Make sure the grommets are symmetrically arrayed, front-to-back, side-to-side.)

Appendix B. Flex Prototype Application Instructions

This appendix appears in its original form, without editorial change.

Instructions for Applying Flexible Straps

(Modular EEG system)



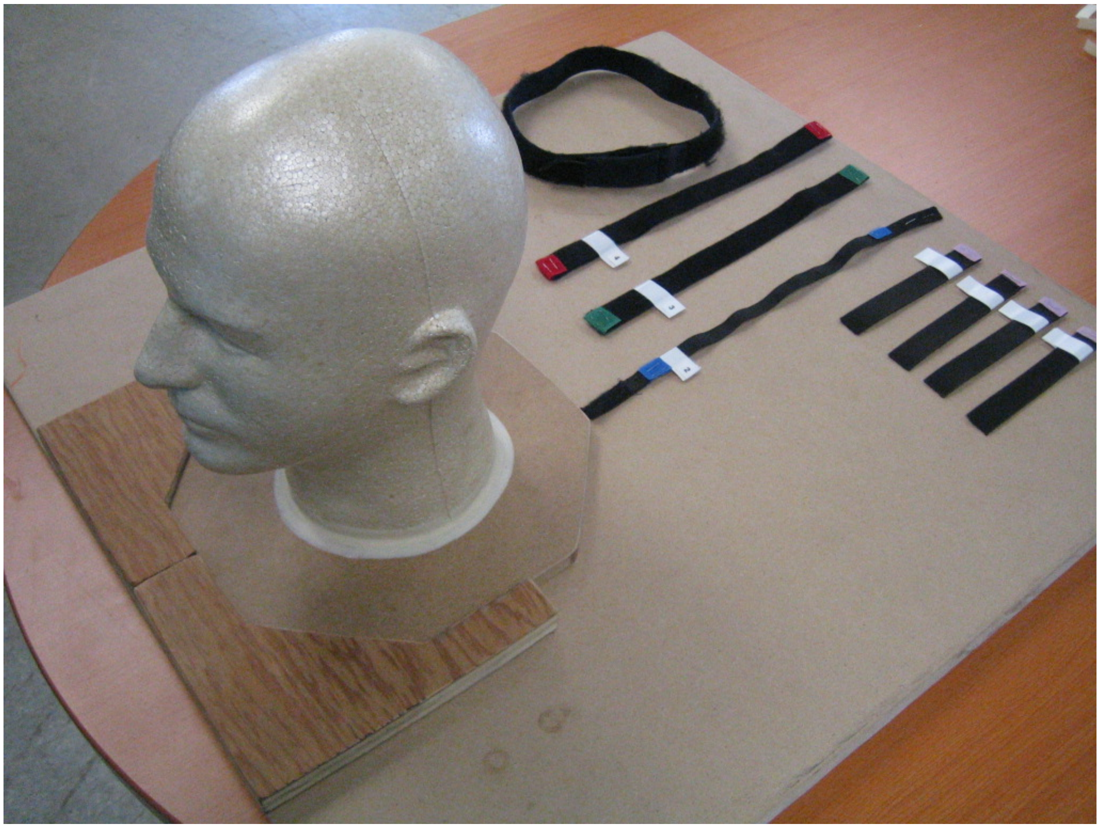
Dr. Scott Kerick

Theodric Feng

David Kuhn

Draft – August 2014

ARL/HRED/TNB



Straps:

Circular (black)

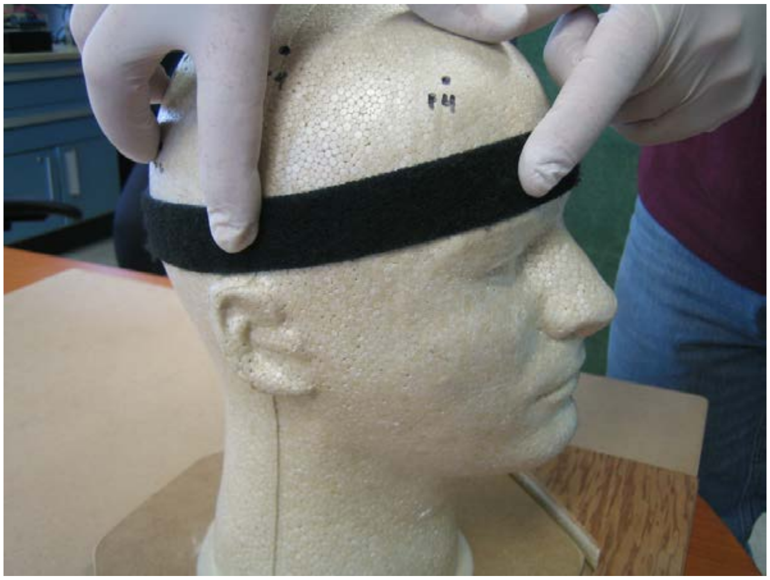
Chin (blue)

Lengthwise (red)

Sideways (green)

Segments (pink)

Step 1



Place circle strap around the head, so that it is just above the eyebrows and ears. Make sure the fuzzy side is facing outward. Align the seam with the nose.

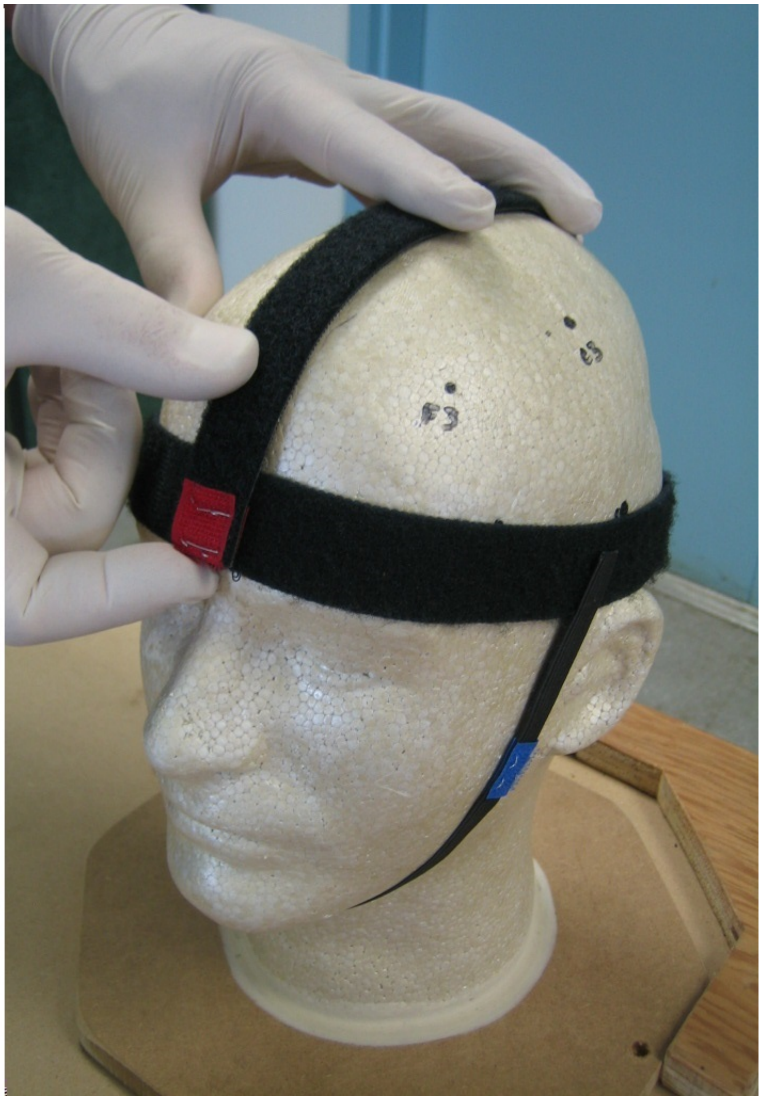
In the back, make sure that the strap covers only part of the circular dent.

Step 2

Attach blue chin strap (#2)

Place under the chin, and attach ends to circle strap, forward of the ear.

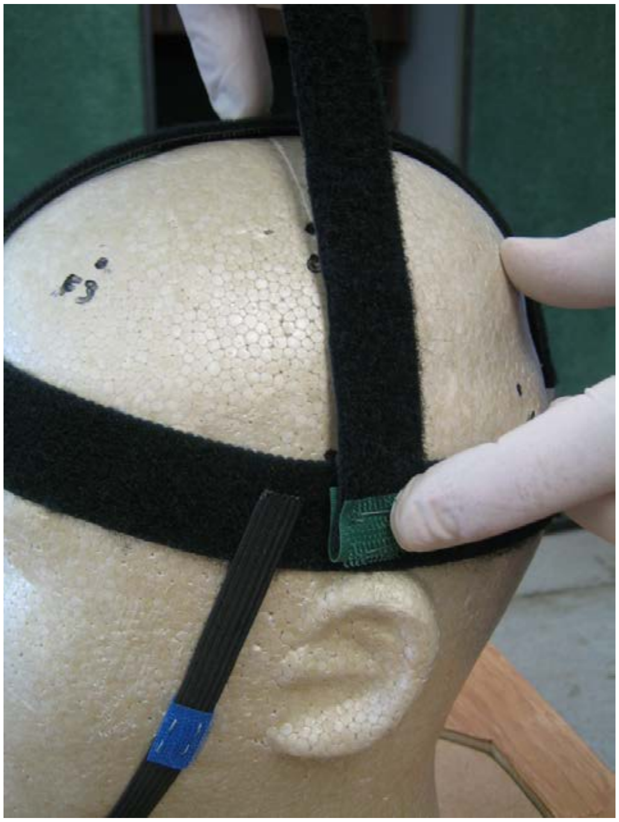
Step 3



Apply the red lengthwise strap (3)

- Place the red strap lengthwise along the top and midline of the head.
- Adhere the ends to front and back of the circle strap. Make sure the red tab is flush with the bottom edge of the circle strap and aligned with the nose.

Step 4

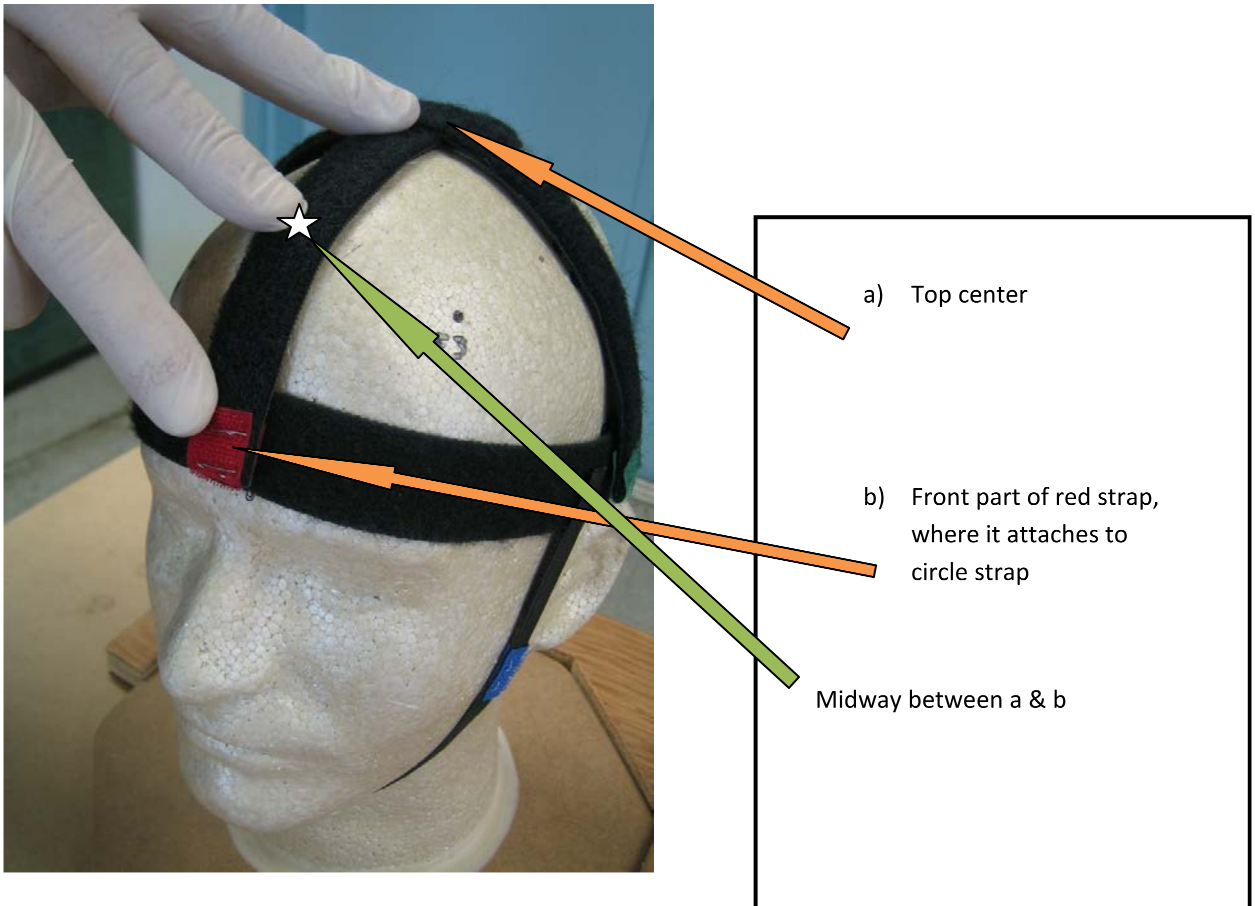


Attach the green strap sideways across the top of the head from ear to ear. Align it to the middle of the ears.

Adhere the ends to the circle strap, on the sides of the head.

Put the green tab flush with the lower edge of the circle strap.

Step 5



Find the midpoint of the front half of the red strap.

The strap half will be bounded by the

a) Spot where the lengthwise and sideways straps meet at the cop of the head, and
b) Spot where the red strap meets the circle strap

Midway between those 2 spots is what you want to identify.

Step 6

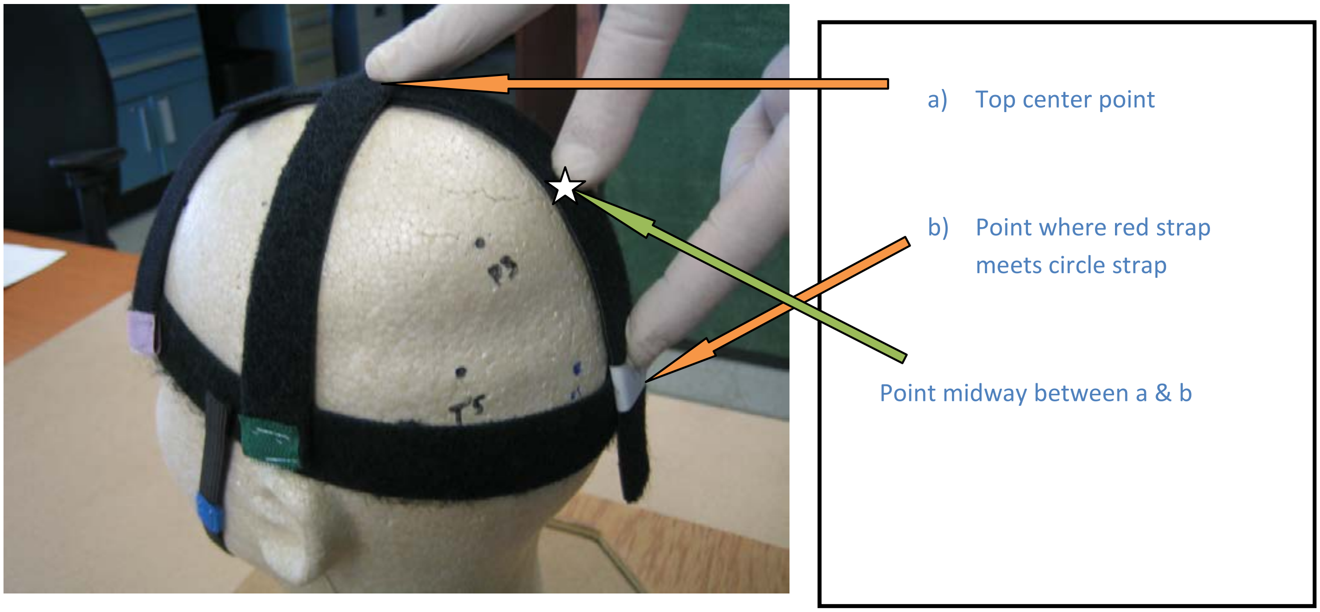
Apply pink strap to frontal midpoints of red and circle strap (right-hand side).

Find midpoint for right front quarter of circle strap. Press pink tag to that spot.

Press other end of pink strap on top of spot where earlier pink strap attaches to red strap.

Step 7

Attaching segment strap to Left rear quarter of the head



Find the midpoint of the rear half of the lengthwise strap, the point midway between

a) The center top of the head (where red and green straps intersect) and

b) The point where the circle and lengthwise straps meet at the back

Step 8

Attaching segment strap to Right rear quarter of head

Apply the pink strap to the rear midpoints of the red and circle strap (right-hand side).

Find the midpoint for the right rear quarter of the circle strap. Press the pink tag to that spot.

Press the other end of the pink strap on top of the spot where the earlier (left) pink strap attaches to the lengthwise strap.

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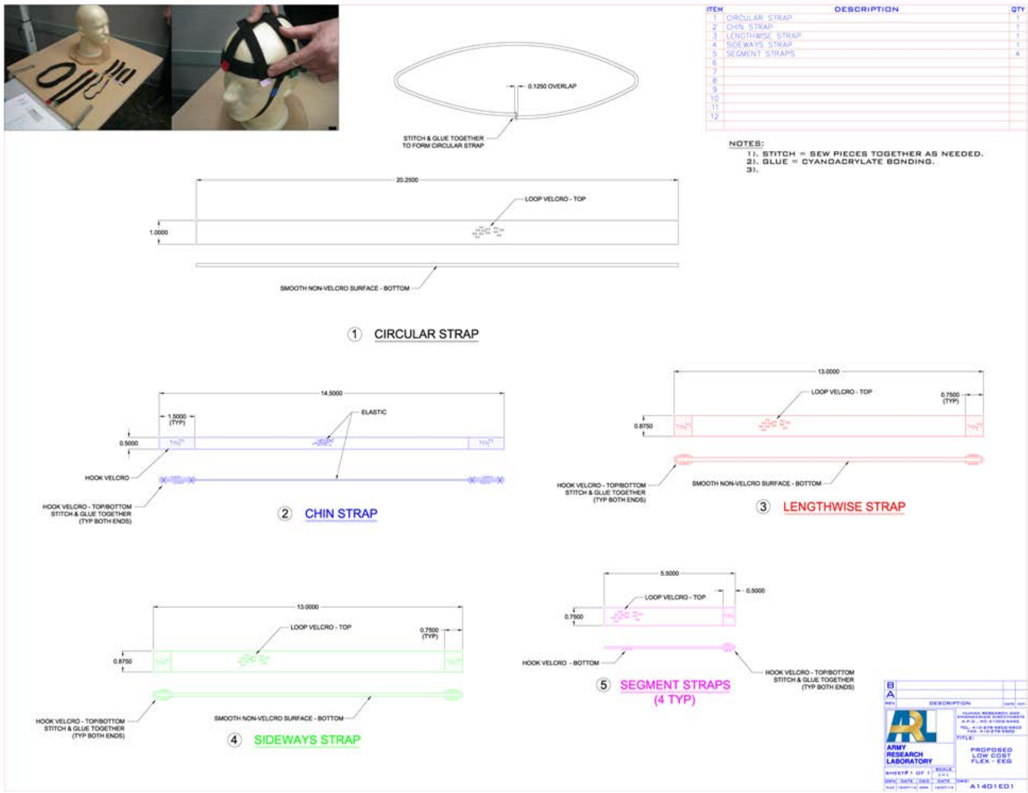
Appendix C. Computer-Assisted Drawing of the Flex System

This appendix appears in its original form, without editorial change.



ITEM
DESCRIPTION
QTY
1 CIRCULAR STRAP 1
2 CHIN STRAP 1
3 LENGTHWISE STRAP 1
4 SIDEWAYS STRAP 1
5 SEGMENT STRAPS 4
NOTES:
1). STITCH = SEW PIECES TOGETHER AS NEEDED.
2). GLUE = CYANOACRYLATE BONDING.
3).
0.1250 OVERLAP
STITCH & GLUE TOGETHER TO FORM CIRCULAR STRAP
20.2500
LOOP VELCRO - TOP
1.0000
SMOOTH NON-VELCRO SURFACE - BOTTOM
1 CIRCULAR STRAP
14.5000
1.5000 (TYP)
ELASTIC
0.5000
HOOK VELCRO
HOOK VELCRO - TOP/BOTTOM STITCH & GLUE TOGETHER (TYP BOTH ENDS)
2 CHIN STRAP
13.0000
LOOP VELCRO - TOP
0.7500 (TYP)
0.8750
HOOK VELCRO - TOP/BOTTOM STITCH & GLUE TOGETHER (TYP BOTH ENDS)
SMOOTH NON-VELCRO SURFACE - BOTTOM
3 LENGTHWISE STRAP
5.5000
LOOP VELCRO - TOP
0.5000
0.7500
HOOK VELCRO - BOTTOM
HOOK VELCRO - TOP/BOTTOM STITCH & GLUE TOGETHER (TYP BOTH ENDS)
5 SEGMENT STRAPS (4 TYP)
13.0000
LOOP VELCRO - TOP
0.7500 (TYP)
0.8750
HOOK VELCRO - TOP/BOTTOM STITCH & GLUE TOGETHER (TYP BOTH ENDS)
SMOOTH NON-VELCRO SURFACE - BOTTOM
4 SIDEWAYS STRAP
B
A
REV
DESCRIPTION
ARMY RESEARCH LABORATORY
TITLE:
PROPOSED LOW COST FLEX - EEG
SHEET# 1 OF 1
SCALE
1=1
DWG
A1401E01

List of Symbols, Abbreviations, and Acronyms

3-D	3-dimensional
ANOVA	analysis of variance
BCI	brain–computer interface
C3	left central
C4	right central
Cz	midline central
EEG	electroencephalograpy
ELPOS	electrode positioning
F3, F7	left frontal
F4, F8	right frontal
FPz	midline frontopolar
Fz	midline frontal
Iz	inion
LPA	left pre-auricular
Nz	nasion
Oz	midline occipital
P3, P7	left parietal
P4, P8	right parietal
Pz	midline parietal
RPA	right pre-auricular
SBIR	Small Business Innovation Research
T7	left temporal
T8	right temporal

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